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Tracking the impacts of recent warming and thaw of permafrost peatlands on aquatic ecosystems: a multi-proxy approach using remote sensing and lake sediments

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Regions within the discontinuous permafrost zone of the southern Northwest Territories (Canada) are experiencing accelerated thaw of permafrost as a result of recent warming. We used remotely-sensed imagery (1947–2012) to track changes in the extent of peat plateau collapse around two study lakes: KAK-1 and TAH-7. Subfossil diatoms were analyzed from sediment cores to reconstruct limnological changes over the past ~300 years and assess whether peatland subsidence affected lake ecology. Extensive peat plateau collapse was evident in catchments between 1970 and present day. In TAH-7, diatom assemblages indicated a substantial increase in coloured dissolved organic carbon coincident with the time of peat collapse, suggesting that permafrost thaw has resulted in increased transport of terrestrial organic matter to the lake. At KAK-1, while also tracking changes linked to climate warming, no changes in diatom assemblages could be linked to peat plateau collapse. Using our combined approaches, we conclude that collapsing peat plateaus may significantly alter aquatic ecosystems, but the impacts of permafrost thaw on aquatic ecosystems in the sporadic discontinuous permafrost zone are complex.

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Introduction

Northern ecosystems are experiencing rapid environmental change (Collins *et al*. 2013). The cryosphere is particularly sensitive, with recent observations of reductions in extent and volume of sea ice (Stroeve *et al*. 2007, 2008), melting of glaciers (Witze 2008, Sharp *et al*. 2011), longer ice-free seasons on freshwater ecosystems (Smol and Douglas 2007a, 2007b), widespread warming of permafrost (Smith and Burgess 1998, Smith *et al*. 2005, Burn and Kokelj 2009) and the northward retreat of the permafrost boundary (Nelson *et al*. 2002). Thawing of permafrost can modify water storage and drainage pathways, including thermokarst lake expansion (Parsekian *et al*. 2011, Sannel and Kuhry 2011), catastrophic lake drainage (Jorgenson and Osterkamp 2005) and by increasing the connectivity of drainage networks in thawing peatlands (Beilman and Robinson 2003, Quinton *et al*. 2011). Thawing of permafrost in glacial tills can significantly increase solute and sediment loading to impacted streams and lakes (Kokelj *et al*. 2009, Kokelj *et al*. 2013) and alter aquatic ecosystems (Thienpont *et al*. 2013). In the boreal forest, fire can play an important role in accelerating permafrost degradation by removing the insulating organic layer (Zoltai *et al*. 1993, Mackay 1995, Yoshikawa *et al*. 2003), and the frequency and intensity of forest fires is also predicted to change with climate warming (Flannigan *et al*. 2009). Organic rich permafrost is widespread throughout the circumpolar north (Tarnocai *et al*. 2009) and its thawing may have a significant impact on the nature and magnitude of dissolved organic carbon (DOC) inputs to northern aquatic ecosystems. Changes in DOC concentrations have important implications for lake ecology: for example, it can alter light penetration in lakes and therefore impact plankton communities (Williamson *et al*. 1996) and can also alter thermal regimes within lakes (Snucins and Gunn 2000). Increasing trends in DOC loading to major northern rivers (Frey and McClelland 2009, Gustafsson *et al*. 2011, Olefeldt *et al*. 2014) has been attributed to permafrost thaw, however there is a paucity of catchment-scale investigations to support these inferences.

Models suggest that, by the year 2100, the global land area underlain by permafrost will be reduced by between 37% and 81% (Collins *et al*. 2013). The circumpolar Arctic is warming faster than the global average (Johannessen *et al*. 2004, Kaplan and New 2006) and, specifically, permafrost-supported peatlands of the Taiga Plains have been shown to be “severely” sensitive to climate change (Kettles and Tarnocai 1999). Investigations based on remotely-sensed images of the Scotty Creek basin, located 50 km south of Fort Simpson within the sporadic discontinuous permafrost zone in the Northwest Territories (NWT), showed that 38% of permafrost in a 1 km^2 study area disappeared between 1947 and 2008, and was accompanied by land subsidence and flooding of peat plateaus (Quinton *et al*. 2011). Models also predict that permafrost in Fort Simpson will almost completely disappear given a 2 °C increase in mean annual air temperature (MAAT) (Wright *et al*. 2000).

How aquatic ecosystems respond to the loss of permafrost in organic rich soils of the sporadic permafrost zone of regions such as the southern NWT remains uncertain. A lack of ecological monitoring data in peatlands and lakes poses a challenge for determining if, how, and when ecosystem conditions have changed. In the absence of direct monitoring data, indirect methods are required. Such approaches include historical aerial photographs and satellite imagery, which can be used to provide information on the last several decades of landscape change within a watershed (e.g. Beilman and Robinson 2003, Quinton *et al*. 2011), and paleolimnological methods, which can be used to track changes in aquatic ecosystems over hundreds to thousands of years through the analysis of proxy data archived in lake sediments (Smol 2008). Diatoms (class Bacillariophyceae), a ubiquitous group of siliceous, microscopic algae that preserve well in sediments, are an important paleolimnological proxy that can be applied to track aquatic ecosystem changes over time (Smol and Stoermer 2010). The vast number of applications for diatoms as biological indicators has been exemplified in many previous studies, including the reconstruction of pH, DOC, and the type of littoral habitat (e.g., Pienitz and Smol 1993, Pienitz *et al*. 1999, Michelutti *et al*. 2003, Myers-Smith *et al*. 2008, Hyatt *et al*. 2011). A recent paleolimnological study in the Mackenzie

Delta uplands, NWT, utilized diatoms to examine changes to lake ecosystems associated with shoreline retrogressive thaw slumping, a spectacular form of permafrost degradation in areas of ice-rich permafrost (Thienpont *et al*. 2013). Macroscopic charcoal (> 125 μm) is also well-preserved in lake sediments and can be applied to track regional fire history. This is important because forest fires can lead to thawing of permafrost through the loss of overlying insulating organic material (Mackay 1995). The integration of multi-proxy paleolimnological studies with remote sensing techniques can provide a comprehensive assessment of environmental change in areas where monitoring data are limited, and is useful for determining the impacts of landscape changes on downstream aquatic ecosystems in the catchment.

To investigate the potential impacts of peatland thaw on aquatic ecosystems at the southern extent of the permafrost boundary we utilized dated lake sediment cores, historical aerial photographs, and recent satellite imagery to track long-term environmental change in the southern NWT. The objectives of this study are to: (1) calculate the spatial extent of peat plateau thaw in the region over the last few decades; and (2) determine how aquatic ecosystems have responded, if at all, to environmental change over the last several hundred years, including recent landscape changes. Two small, shallow lakes and their catchments were analyzed in this study. One lake (KAK-1, unofficial name) has a large bog present on the northwestern margin of the lake that we hypothesized may be indicative of lake expansion as a result of loss of permafrost and regional warming (e.g., Parsekian *et al*. 2011). A second lake (TAH-7, unofficial name) has no visible bog or vegetation mat on its shoreline. Aerial photographs dating back to the mid-1900s were used to investigate potential changes in lake size and extent of collapsed peat scars. Diatoms preserved in lake sediment cores were used as indicators of limnological change, and macroscopic charcoal was analyzed to reconstruct regional forest fire history. The data provided by the study will improve our understanding of the impacts of permafrost degradation on aquatic ecosystems at the southern extent of the permafrost boundary, as it is projected to move northward under future climate warming scenarios.

Material and methods

Site description

The two study lakes are located within the Tathlina Plain of the Taiga Plains Mid-Boreal Ecozone (Ecosystem Classification Group 2007) southwest of Great Slave Lake, in close proximity to Tathlina and Kakisa lakes (Fig. 1). Surficial geology in this region is characterized by extensive glacial till and lacustrine plains, organic blankets and alluvial deposits (Ecosystem Classification Group 2007). This region is within the sporadic permafrost zone, where permafrost underlays 10%–50% of the land surface and is generally restricted to peat plateaus (Heginbottom *et al*. 1995). Permafrost is maintained beneath these peat plateaus as a result of the thermal offset related to the thermal properties of peat (Brown 1970, Burn and Smith 1988). A positive feedback occurs as the accumulation of ice beneath these peat plateaus leads to the elevation of these areas above the surrounding landscape, sustaining drier and colder soil conditions (Zoltai 1972).

The Taiga Plains Mid-Boreal ecozone is subject to the mildest climate in the NWT and mean annual air temperatures (MAAT) in January range from –25.5 to –28 °C and from 15.5 to 16.5 °C in July (Ecosystem Classification Group 2007). Temperature records from the Hay River Climate Station show a significant warming trend in MAAT beginning in at least 1896 (Fig. 2). Climate reconstructions indicate that the southern regions of the NWT have been warming since the mid-19th century (Moser *et al*. 2002, Rühland and Smol 2005). Mean annual precipitation is between 310 and 410 mm, with the wettest period from June to August (Ecosystem Classification Group 2007).

KAK-1 (61.038056°N, 117.551111°W) is located north of Kakisa Lake, near the community of Kakisa (Fig. 1). TAH-7 (60.570567°N, 116.904032°W) is located east of Tathlina Lake, approximately 63 km southeast of KAK-1 (Fig. 1). Both lakes have a surface area < 4 ha,

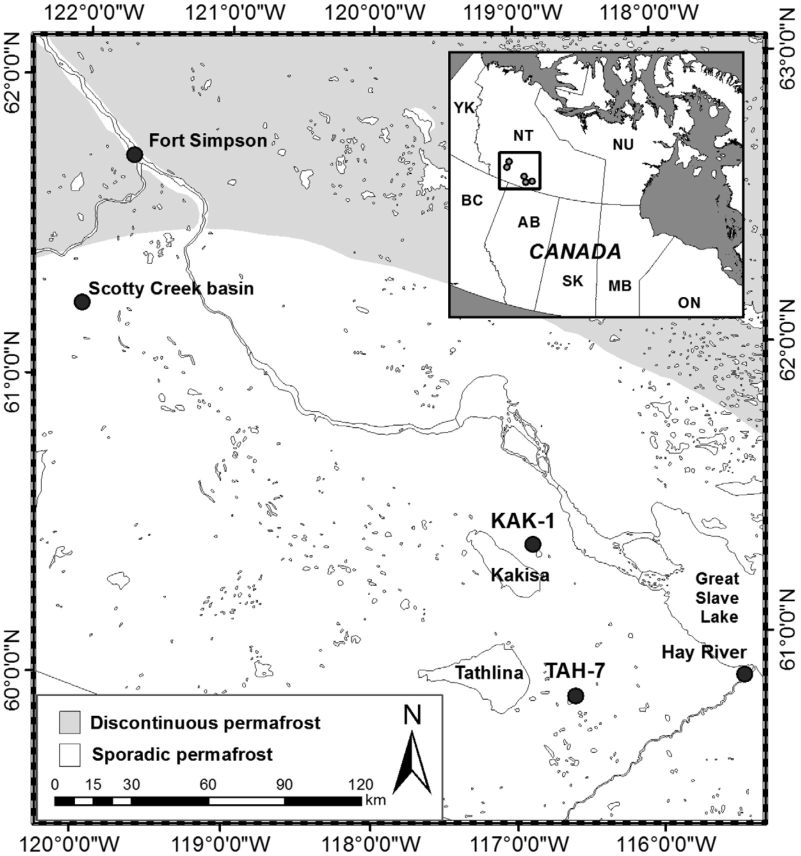

Fig. 1. Locations of the study lakes, KAK-1 and TAH-7, and the Hay River Climate Station in the Northwest Territories.

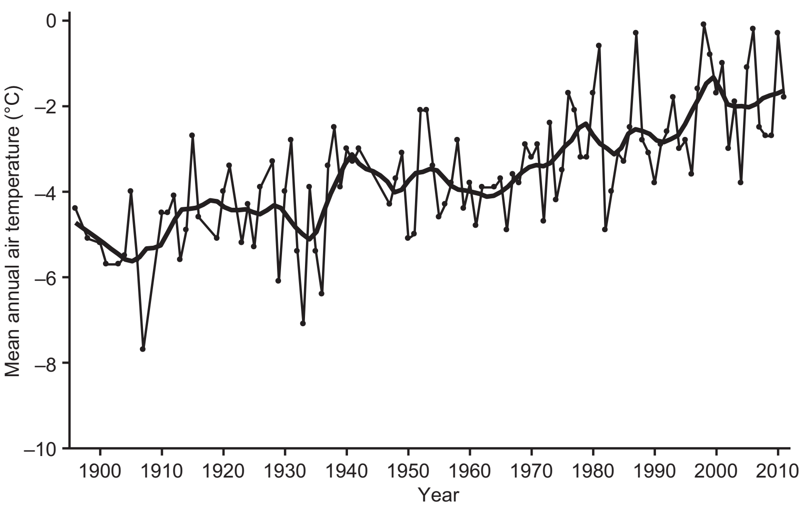

Fig. 2. Mean annual air temperature from 1896 to 2011 from the Hay River Climate Station including LOESS smoothed line. A Mann-Kendall test shows a significant positive trend in MAAT (τ = 0.523, p < 0.001, n = 102).

and a maximum depth < 2 m. TAH-7 is circumneutral (pH = 7.58), meso-eutrophic (total phosphorus (P_{tot} = 44 μg l^{-1}), has high dissolved organic carbon and high colour (DOC = 46.8 mg l^{-1}; colour = 91 TCU) (Table 1). KAK-1 is slightly alkaline (pH = 8.31), oligotrophic (P_{tot} = 7 μg l^{-1}) and also has high DOC (36.1 mg l^{-1}). Colour is lower (32 TCU) relative to TAH-7 (Table 1).

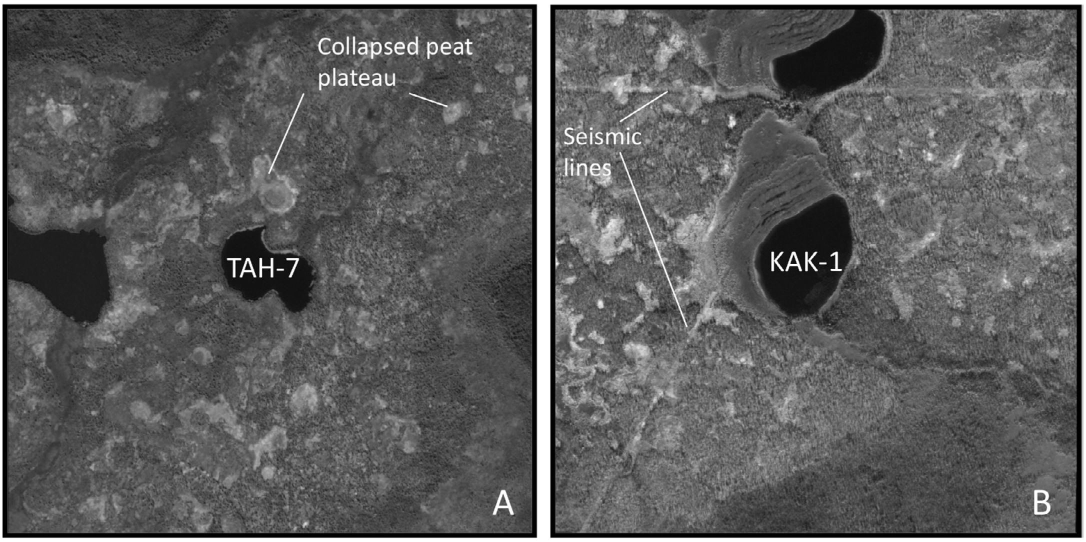

Fig. 3. High resolution (0.5 m) WorldView satellite imagery of the two 1 km^2 study areas, including (**A**) TAH-7, and (**B**) KAK-1. Examples of peat plateau and collapse scar features that were mapped by aerial imagery analysis are identified.

Aerial imagery analysis

We examined a series of historical aerial photographs and recent satellite imagery to determine if the area occupied by peat plateaus has changed within the last 65 years. Permafrost-supported peat plateaus are elevated above the surrounding landscape, and in the southwestern NWT are often populated by stands of black spruce. The degradation of permafrost beneath these peat plateaus leads to collapsed peat scar features that are easily identifiable in aerial images because permafrost thaw ultimately transforms peat plateaus into treeless bogs and wetlands (Jorgenson *et al*. 2001, Quinton *et al*. 2011). High resolution (0.5 m) single band 8-bit WorldView satellite images were obtained in August–September 2012, along with three series of historical high-resolution (0.3–0.7 m) black and white aerial photographs (1947–1983), and a 1 km^2 area centered on the study lakes was selected for analysis (Fig. 3). The historical aerial photographs were orthorectified using the 2012 WorldView satellite imagery via aerial triangulation (RMSE: 0.34–0.74). The perimeters of the individual study lakes and collapsed permafrost features were manually digitized using ArcMap (version 10) for each of the time series photographs and satellite images. There is evidence of anthropogenically induced land cover change as a result of linear disturbance in the KAK-1 study area. These collapsed features were included in the areal calculation of total collapsed features for this study area. Collapsed permafrost features were not digitized from the 1947 aerial photograph for the catchment of KAK-1 due to poor image quality, however, it was possible to calculate lake area due to the high contrast

Table 1. Water chemistry of study sites, KAK-1 and TAH-7 evaluated in September 2013.

	KAK-1	TAH-7
pH	8.3	7.6
Dissolved organic carbon (DOC,mg l^{-1})	36.1	46.8
True colour (TCU)	32	91
Specific conductivity (at 25°C) (μS cm^{-1})	161	105
Total phosphorus (P_{tot}, μg l^{-1})	7.0	44.0
Total nitrogen (N_{tot}, mg l^{-1})	1.1	1.7
Total dissolved solids (mg l^{-1})	162	140
Calcium (mg l^{-1})	29.7	18.9
Chloride (mg l^{-1})	0.7	0.7
Potassium (mg l^{-1})	0.5	0.1
Sodium (mg l^{-1})	3.2	0.5
Sulphate (mg l^{-1})	1.0	1.0
Total iron (mg l^{-1})*	1.0	0.2

* measured in March 2012.

between land and water features in the image. Manual digitization of features was validated by a separate operator for a subset of the 1 km^2 study areas. Results indicate 97% correspondence between the two operators.

Lake sediment cores

In order to examine limnological changes, sediment cores were collected from KAK-1 and TAH-7 in March 2012 using a Glew (1989) gravity corer (internal diameter 7.62 cm) and intervals were extruded at 0.5 cm resolution using a Glew (1988) vertical extruder. Sediment samples were placed directly into individual Whirl-Pak® sample bags. To establish a core chronology, ^{210}Pb dating was completed at the University of Ottawa using an Ortec High Purity Germanium Gamma Spectrometer (Oak Ridge, TN, USA) and the constant rate of supply (CRS) model (Appleby and Oldfield 1978). Certified Reference Materials obtained from the International Atomic Energy Association (Vienna, Austria) were used for efficiency corrections, and results were analyzed using ScienTissiME (Barry's Bay, ON, Canada).

Diatom slides were prepared according to standard methods outlined in Battarbee *et al.* (2001). In order to isolate diatoms, sediments were digested using a 1:1 (molecular weight) mixture of nitric and sulfuric acids. The mixture was placed in an 80 °C water bath for 3–4 hours in order to digest the organic matrix. Samples were rinsed with deionized water daily for 7 days, with at least 22 hours between rinses to allow for diatom settling. Once samples reached a neutral pH (~7), they were plated on microscope coverslips. Dry coverslips were mounted onto microscope slides using Naphrax®, a mounting medium with a high refractive index, ideal for viewing diatoms through a light microscope. Diatom slides were analyzed using a Leica DMRB light microscope equipped with differential interference contrast (DIC) filters, which increases contrast of specimens to aid in identification. Slides were viewed under an oil immersion lens at 1000× magnification. Diatoms were identified to the species level according to numerous diatom reference books (e.g., Krammer and Lange-Bertalot 1997, 1999, 2000). A minimum of 350 diatom valves were counted per interval up to a maximum of 521 valves, with counts generally between 400 and 500 valves per interval.

For macroscopic charcoal analysis, a volume of 1 cm^3 of sediment was soaked for at least 24 hours in a hexametaphosphate solution (Bamber 1982), before they were gently rinsed through a 150 μm sieve. Macroscopic charcoal is separated from microscopic charcoal (< 150 μm) because it takes more energy to transport from the location of the fire event and therefore better represents local fires. The remaining macroscopic charcoal was rinsed into a Petri dish with a square grid pattern and fragments were counted. Charcoal fragments were tallied by examination under a Nikon SMZ800 stereoscope at a magnification of 6–40×.

Visible reflectance spectroscopy (VRS) was used to reconstruct sedimentary chlorophyll *a* (chl-*a*) according to Michelutti *et al.* (2005, 2010). This method has been shown to be an accurate representation of trends in lake primary production changes through time (Michelutti *et al.* 2010). For VRS-inferred chl-*a*, freeze-dried sediment intervals from both lakes were sieved through 125 μm mesh and analyzed using FOSS NIRSystem Model 6500 rapid content analyser. VRS chl-*a* concentration was calculated using a linear regression equation (Michelutti *et al.* 2005).

Statistical analyses

Relative abundances (%) of diatom species were calculated and the most abundant taxa were graphed in biostratigraphies using Tilia 1.7 (Grimm 2011). A constrained incremental sum of squares (CONISS) cluster analysis was performed on the complete diatom datasets in order to identify stratigraphic zones of similar diatom assemblages in each core (Grimm 1987), and a broken stick model was used to assess the significance of CONISS-delineated zones (Bennett 1996). Very few rare species in each core (< 1% abundance) were present, so a cut-off criterion to eliminate rare taxa was not used. Species diversity was calculated using the Hill's N2 index (Hill 1973) in the program CANOWIN 4.51 (ter Braak and Šmilauer 2003).

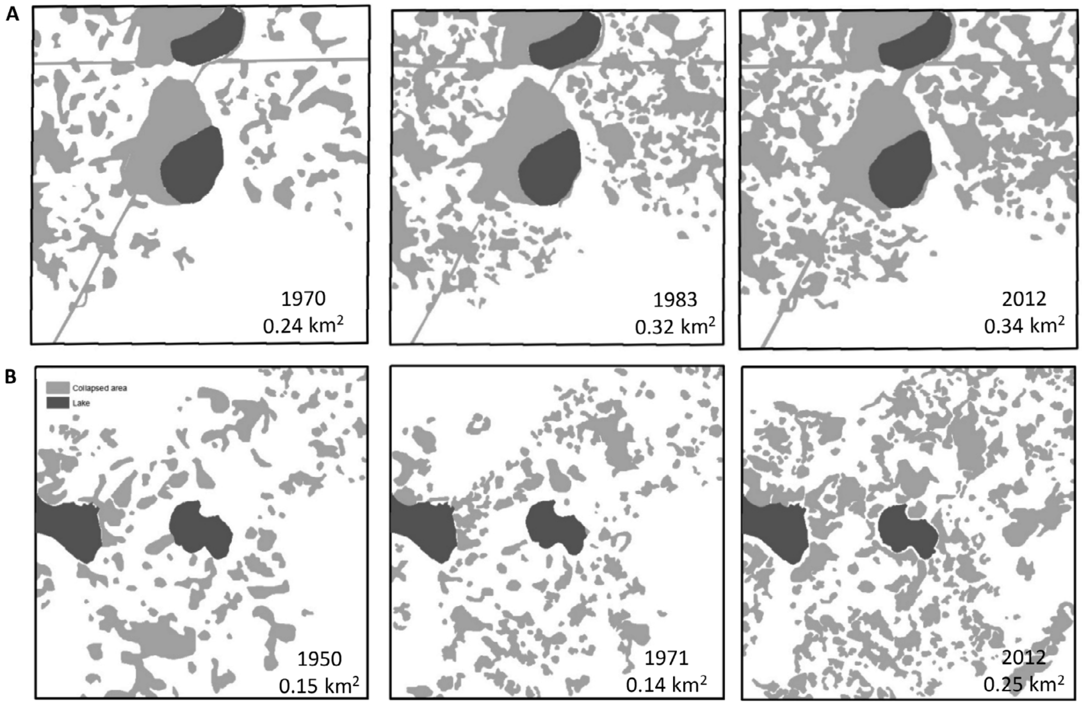

Fig. 4. The area occupied by collapse scars in a 1 km^2 area centered on (**A**) KAK-1 in 1970, 1983, and 2012; and (**B**) TAH-7 in 1950, 1971, and 2012.

Results

Remote sensing

Remote sensing analyses indicated that the surface area and the shape of the two study lakes did not change substantially over the time series of remotely sensed images (Table 2). Comparison of historical remote sensing imagery indicates a substantial decrease in the area of peat plateau and an increase in the area of collapsed "fen" type environments in both study catchments. The area of collapsed features in the KAK-1 catchment increased from 0.24 km^2 in 1970 to 0.33 km^2 in 2012, representing an increase of 28% (Table 2 and Fig. 4A). Increase in surface area of collapsed features was greatest between the 1970 and 1983 aerial photographs (Table 2 and Fig. 4A). Within the 1 km^2 study area around TAH-7, the extent of collapsed permafrost features increased from

Table 2. Lake area and extent of collapsed features mapped for the two study areas. Note: the extent of collapsed features was not calculated in 1947 at KAK-1 due to poor image quality.

	NAPL* air photo roll and number	Acquisition date	Lake area (ha)	Extent of collapsed features (m^2)
TAH-7	NA	19 Aug. 2012	1.81	251429
	A22439-85	29 Aug. 1971	1.80	135775
	A12537-429	29 May 1950	1.81	146067
KAK-1	NA	17 Sep. 2012	3.00	332798
	A26304-49	25 June 1983	3.00	317283
	A21530-14	29 Aug. 1970	2.94	240379
	A11001-40	19 July 1947	2.93	NA

* National Air Photo Library, Natural Resources Canada, Ottawa, ON.

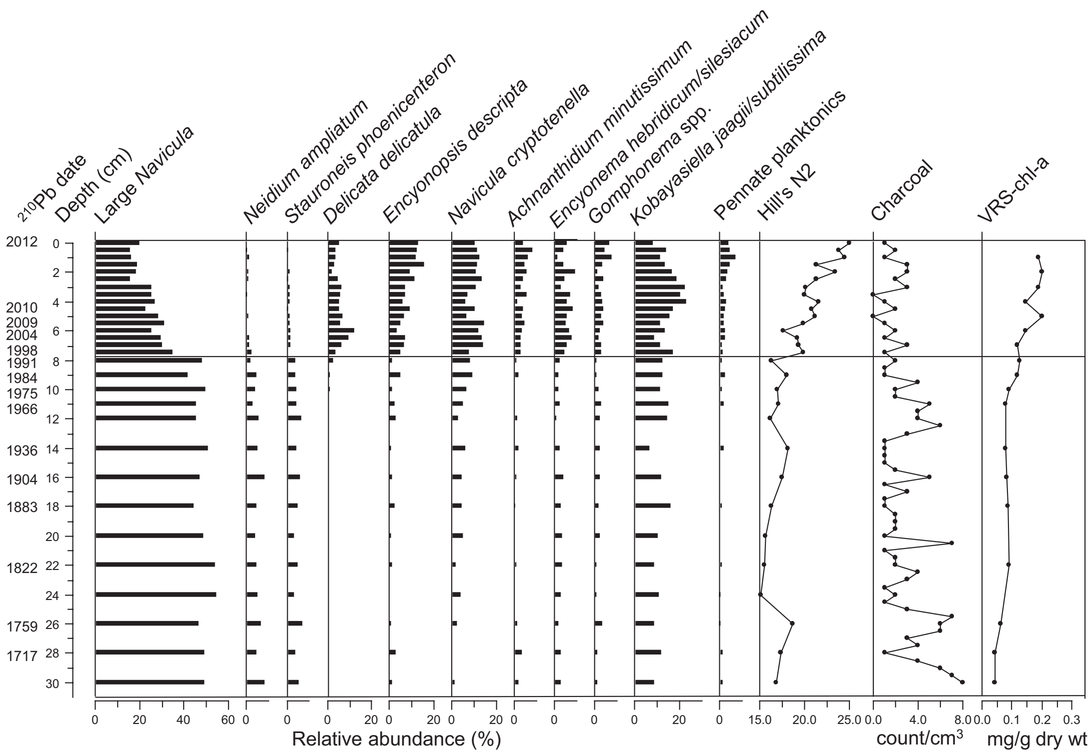

Fig. 5. Relative frequency diagram for KAK-1 showing changes in the dominant diatom taxa, as well as Hill's N2 values, the concentration of charcoal particles, and visible reflectance spectroscopy-inferred chlorophyll *a* (VRS-chl-*a*). Vertical lines represent biostratigraphic zones based on CONISS cluster analysis. ^{210}Pb dates are shown to the left, with dates older than 1904 based on extrapolation and so should be interpreted cautiously.

0.15 km^2 in 1950 to 0.25 km^2 in 2012, representing a 44% increase in collapsed permafrost features (Table 2 and Fig. 4B). The bulk of the difference in collapsed permafrost features occurs between the two most recent images, 1971 and 2012 (Table 2 and Fig. 4B).

Lake sediment cores

KAK-1

Throughout most of the sediment record, spanning the approximate time frame of 1600–1991 (8–30 cm), the diatom assemblage was dominated by large *Navicula* species (*N. wildii*, *N. vulpina*, *N. leptostriata*, *N. radiosa*), as well as other large benthic species including *Neidium ampliatum*, and *Stauroneis phoenicenteron* (Fig. 5). A significant shift in diatom species assemblage (identified based on CONISS and the broken stick model) occurred at 8 cm (~1991), characterized by decreases in large *Navicula* taxa, increases in *Delicata delicatula*, *Encyonopsis descripta*, *Navicula cryptotenella*, *Achnanthidium minutissimum* and *Encyonema* species (*E. hebridicum* and *E. silesiacum*), and small increases in *Gomphonema* species, *Kobayasiella* species, and pennate planktonic species (Fig. 5). Additionally there is an overall increase in Hill's N2 species diversity and primary production (inferred from sedimentary VRS-chl-*a*) during this time period (Fig. 5). Macroscopic charcoal concentrations were low throughout the sediment record, with no discrete charcoal peaks, which suggests no large fire events occurred in the catchment over the last ~400 years (Fig. 5).

TAH-7

Several shifts in diatom species assemblages

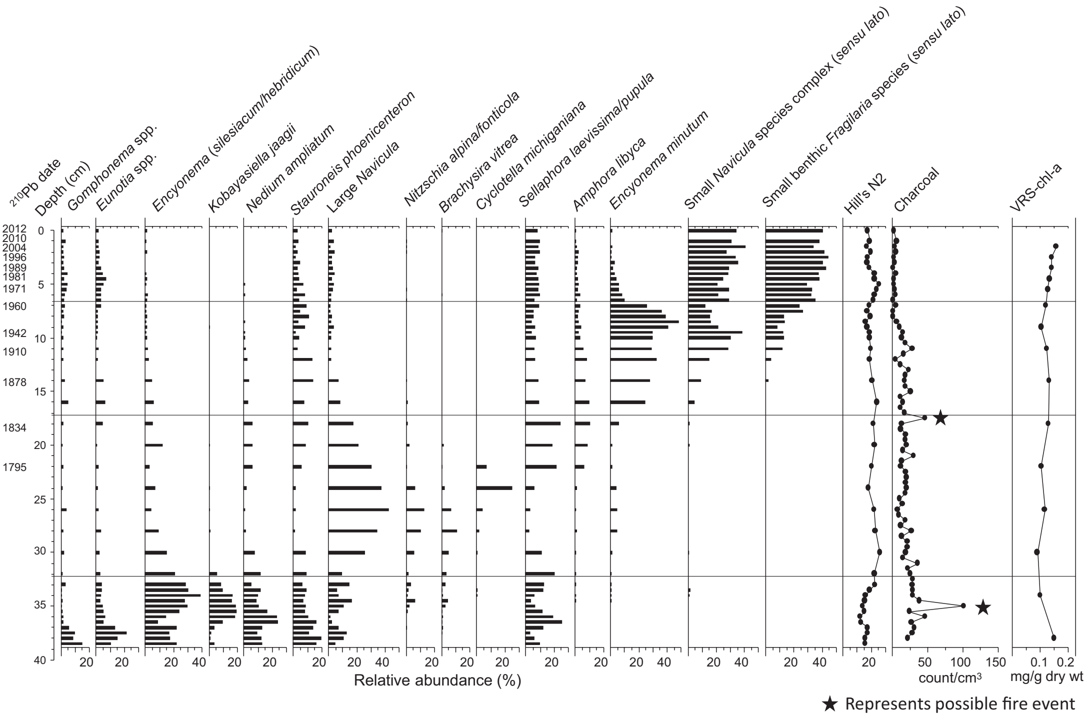

Fig. 6. Relative frequency diagram for TAH-7 showing changes in the dominant diatom taxa, as well as Hill's N2 values, the concentration of charcoal particles, and visible reflectance spectroscopy-inferred chlorophyll *a* (VRS-chl-*a*). Horizontal lines represent biostratigraphic zones based on CONISS cluster analysis. ^{210}Pb dates are shown to the left, with dates older than 1909 based on extrapolation and so should be interpreted cautiously.

were evident in TAH-7 over the last several hundred years of its history (Fig. 6). In the oldest portion of the sediment core record (39–32 cm), the diatom assemblage was dominated by epiphytic species such as *Gomphonema* and *Eunotia* species, as well as several other benthic taxa, most notably *Encyonema hebridicum*, *E. silesiacum*, *Kobayasiella jaagi*, *Neidium ampliatum* and *Stauroneis phoenicenteron*. Above 30 cm, decreases in these epiphytic taxa were observed, along with corresponding increases in large *Navicula* species (*N. wildii*, *N. cryptotenella* and *N. radiosa*), *Nitzschia fonticola* and *N. alpina*, *Brachysira vitrea*, and the planktonic *Cyclotella michiganiana*. *Achnanthidium minutissimum, Sellaphora pupula*, *S. laevissima*, and *Amphora libyca* also appear briefly. Between 17–6.5 cm (~1845 to 1962), an increase in *Encyonema minutum* was observed along with a complex of small *Navicula* species *sensu lato* (*Sellaphora seminulum*, *Naviculadicta absoluta*, *Naviculadicta pseudoventralis* and *Navicula minima*). Small benthic *Fragilaria* species *sensu lato* (*Staurosira venter* and *Staurosirella pinnata*) are also first recorded during this time. The most recent diatom assemblage shift occurred ~1962 (6.5 cm) and was characterized by a large relative decrease in *Encyonema minutum* and continued increases in small benthic *Fragilaria*. Despite several shifts in diatom assemblages, no clear changes in species diversity or inferred chl-*a* were recorded (Fig. 6). Based on total charcoal counts, a possible fire event occurred at 35 cm and potentially a second, smaller fire at 17.5 cm (~1845) (Fig. 6).

Discussion

KAK-1

Sedimentary diatom assemblages from KAK-1 recorded fairly stable lake conditions until recently (~1991). A trend toward higher species diversity (as indicated by Hill's N2), including an increase in attached species (e.g. *Encyonema* species, *Gomphonema* species, and *Delicata delicatula*), tracks the development of a more complex periphytic habitat in the lake. This trend has been frequently observed in many northern lakes and ponds, and is indicative of warming air temperatures and associated limnological changes, such as a decreased length of seasonal ice cover, longer growing seasons, and more developed littoral zones with increased diversity of substrates for diatom colonization (e.g. Smol and Douglas 2007a, Vincent 2009, Rühland *et al*. 2013), which is further corroborated by an increase in overall primary production inferred using sedimentary VRS-chl-*a*.

Evidence from remote sensing data and aerial photographs indicate that there has been no thermokarst expansion of KAK-1 at least since 1947, and the large bog present on the margin of this lake has been present since the beginning of the aerial photograph record in 1947. This is supported by the sedimentary diatom record, which showed no evidence that lake expansion and formation of a floating vegetation mat has occurred in the recent past. The aerial images do show that there has been significant degradation and collapse of permafrost peat plateau since the aerial photograph in 1970; however, the presence of peat scars in the earliest photograph suggests that landscape alterations began prior to the aerial photograph record, and this region has likely been experiencing these types of landscape change for ~150 years (Beilman and Robinson 2003, Halsey *et al*. 1995). A significant shift in diatom assemblage occurred ~1991, but these changes are not necessarily indicating limnological change occurring as a result of thawing permafrost within the catchment and altered terrestrial run-off, as similar diatom assemblage changes have been observed throughout northern latitude regions in response to longer open-water seasons (e.g., Smol and Douglas 2007a, Vincent 2009). Both our remote sensing and paleolimnological data provide evidence that terrestrial and aquatic ecosystems have been changing in this area since the late 20th century, likely a result of recent climate warming. However, we record no strong evidence that catchment changes at KAK-1 are altering its limnology, and instead the diatom shifts are most likely tracking decreased ice cover and associated limnological changes.

TAH-7

Diatom assemblages recorded several dynamic periods of limnological change in TAH-7 over the last several hundred years. The dominant taxa in the earliest part of the record (below 32 cm core depth), *Eunotia*, *Gomphonema* and *Sellaphora* species, are most often recorded in moist environments or very shallow lake environments compared to other species (van Dam *et al*. 1994), suggesting drier conditions at this time (exact dates are unknown, as this period is beyond the limits of the ^{210}Pb chronology, but clearly pre-date AD 1850). Similarly, *Kobayasiella jaagii*, *Encyonema silesiacum* and *E. hebridicum*, diatoms commonly attached to submerged vegetation, were present in high abundances during this period, also supporting an inference of shallower water depths. The largest charcoal peak observed in the record was also observed during this time, indicating that a large fire occurred in the surrounding area, also consistent with a drier climate. At 32 cm, *Eunotia*, *Gomphonema*, *Sellaphora* and *Encyonema* species, as well as *Kobayasiella jaagii*, decline and are replaced by taxa that indicate a transition from a marshier environment to a lake environment more similar to what is observed today, implying a wetter climate, including large benthic *Navicula* species. The appearance of the planktonic taxon *Cyclotella michiganiana* indicates a deeper water body capable of supporting open water diatom taxa during this period.

At 17.5 cm (~1845) there is a notable shift toward an assemblage dominated by small *Navicula* species *sensu lato* and *Encyonema minutum*, coincident with a decrease in large *Navicula* and *Sellaphora* taxa. This timing is consistent with a peak observed in the charcoal record, which may represent a local fire event. Forest fires can mobilize nutrients in the soils, as well as initiate permafrost degradation, and as a result have the potential to alter water chemistry of lakes within the catchment (Lamontagne *et al*. 2000, McEachern *et al*. 2000, Kokelj *et al*. 2005). These species may therefore be responding to water chemistry changes including nutrient inputs coming in from the catchment. Although it is tempting to conclude that a forest fire resulted in water chemistry and diatom assemblage changes, this region was likely also beginning to undergo climate warming at this time (Moser *et al*. 2002, Rühland and Smol 2005), making it challenging to determine if a forest fire or a warming climate is the primary driver of these biological changes. The decreased abundance of large *Navicula* taxa coincident with increased small, periphytic species abundance is similar to the recent changes recorded in KAK-1, and inferred to be as a result of recent climate warming, potentially lending support for this as a mechanism of the changes observed in TAH-7 beginning in the mid 1800s.

Diatom assemblage changes were observed beginning at 10 cm (~1940) that may suggest a response to changing dissolved organic carbon (DOC) concentrations and light conditions in TAH-7. Specifically, a sustained decrease in *Encyonema minutum* occurred, coincident with an increase in relative abundance of small *Navicula* species and small benthic *Fragilaria sensu lato* taxa, which were first recorded at approximately 14 cm (late 1800s) but increased markedly after 10 cm (~1950). Based on present-day water chemistry and field observations, TAH-7 is highly coloured, and thus experiences very low light penetration. Decreasing light penetration that occurs as a result of increasing coloured DOC would limit available habitat for species that are unable to move into the photic zone, such as *Encyonema minutum*, which has been found to have a low water colour optima and tolerance (Fallu *et al*. 2002), as well as the macrophytes that they live on. Subsequently, species that are competitive under low-light conditions, such as small benthic *Fragilaria* species (Lotter and Bigler 2000, Smol *et al*. 2005), would be able to flourish. Previous studies from other northern regions have also shown a link between high DOC and *Fragilaria* (Pienitz and Smol 1993, Pienitz *et al*. 1999, Bouchard *et al*. 2013). In a diatom-based study from upland lakes in the Mackenzie Delta region that tracked the impact of rapid permafrost thaw in the form of shoreline retrogressive thaw slumps on lake ecosystems, diatom assemblage changes were shown to be strongly related to aquatic habitat availability mediated through light conditions (Thienpont *et al*. 2013). Permafrost thaw slumping results in rapid increases in water clarity (decreased DOC), and thus lakes with active or stable thaw slumps can be significantly less coloured than unimpacted lakes (Kokelj *et al*. 2009). This has been shown to result in significant increases in macrophyte development (Mesquita *et al*. 2010), and lead to increased periphytic diatom taxa abundance (Thienpont *et al*. 2013). The changes observed after ~1942 in TAH-7 likely represent an analogous, opposite response to peat subsidence and increased run-off of coloured organic matter to the lake, which resulted in decreased light penetration, a decrease in *E. minutum* and coincident increase in small benthic *Fragilaria* taxa capable of thriving under low-light conditions. Recent inferred increases in chl-*a* concentrations were minimal for TAH-7, in contrast with many northern aquatic ecosystems impacted by climate warming (Michelutti *et al*. 2005, Rühland *et al*. 2013), including KAK-1, which showed marked increases in primary production. Decreasing light penetration in TAH-7 would limit primary production, and may explain why a muted trend in inferred sedimentary chl-*a* concentrations was found.

The most recent changes in the diatom species assemblage overlaps, or slightly pre-dates, the remote sensing record (1950–2012), and thus limnological changes inferred from diatoms can be compared to landscape changes occurring in the catchment. Interestingly, aerial imagery analysis showed collapsed peat scars in the earliest image , with little change between 1950 and 1970, followed by large increases in collapsed peat scars between 1970–2012, providing evidence of extensive permafrost degradation in recent decades. This corresponds to the continued increase in small benthic *Fragilaria* taxa observed above 6–7 cm. Taking into account the uncertainties in the ^{210}Pb dating profile, this provides further evidence for the potential of permafrost degradation and peat plateau collapse to result in increased lakewater colour. Collapsed peat plateaus may have changed drainage patterns in this region, and resulted in increased run-off of coloured, terrestrial organic matter into TAH-7 (Frey and McClelland 2009, Bouchard *et al*. 2013).

Conclusions

Our paleoenvironmental data show that the southern NWT is in a period of rapid environmental change. The two lakes studied exhibited divergent trajectories of change, with diatom assemblages in KAK-1 recording only very recent changes, and TAH-7 diatoms indicating a longer and more dynamic history of environmental change. Based on aerial imagery analysis, it is evident that the degradation of permafrost peat plateaus predates the aerial photograph record, as collapsed peat scars are evident in the earliest aerial photographs. Our data show that the degradation of peat plateaus increased through the air photo record and, consistent with rates of warming air temperatures, has been greatest in both catchments since 1970. These findings are similar to that of Beilman and Robinson (2003) and Quinton *et al*. (2011) who documented plateau collapse for similar time periods for other sites within the same region using remote sensing techniques. Landscape processes (e.g., forest fires and permafrost thaw) may have had a significant influence on the limnology of TAH-7 through increases in nutrient and DOC run-off. In contrast permafrost thaw does not appear to have significantly altered the limnology of KAK-1, but rather diatom assemblages appear to be responding to effects related to regional warming, such as the development of a longer growing season and more complex habitat linked to declining ice cover.

The cumulative stressors that drive changes in lake ecology can make it challenging to attribute specific causes to the impacts that have been inferred from paleolimnological data. Our results show that the impacts of permafrost thaw on aquatic ecosystems in the sporadic discontinuous permafrost zone are complex, but that, as hypothesized, there is the potential for the degradation of peat plateaus to significantly alter the delivery of terrestrial organic matter to lakes. In TAH-7, paleolimnological data recorded aquatic changes that are coincident with the landscape alterations determined by remote sensing. Additionally, the use of charcoal analysis to infer local fire events provides some evidence that forest fires can impact lake ecology and may have played a role in accelerating permafrost degradation in this region. This study highlights the value of integrating multiple proxies and methodologies for inferring past environmental change, such as remote sensing and paleolimnology, in order to provide insights into the role landscape changes play in altering aquatic ecosystems.

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